Fermi National Accelerator Laboratory

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Cryogenic Process Simulation

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Introduction

Combining accurate fluid property databases with a commercial equation-solving software package running on a desktop computer allows simulation of cryogenic processes without extensive computer programming. Computer simulation can be a powerful tool for process development or optimization. Most engineering simulations to date have required extensive programming skills in languages such as Fortran, Pascal, etc. Authors of simulation code have also usually been responsible for choosing and writing the particular solution algorithm. This paper describes a method of simulating cryogenic processes with a commercial software package on a desktop personal computer that does not require these traditional programming tasks. Applications include modeling of cryogenic refrigerators, heat exchangers, vapor-cooled power leads, vapor pressure thermometers, and various other engineering problems.

Modeling Thermodynamic Systems

Sets of equations can accurately describe the behavior of many engineering systems. A commercial software package called Engineering Equation Solver© (EES) has been adapted at Fermi National Accelerator Laboratory to simulate helium cryogenic systems . EES uses a modified Newton's method with sparse matrix techniques to solve systems of non-linear equations, and can be used in either a Macintosh or IBM environment. [1]

For a given problem, the first steps are to make reasonable simplifying assumptions and write a set of equations describing the behavior of the system. The equations are then typed into the "Equations" window of EES along with some boundary conditions, as shown in Figure 1. Initial guesses are specified, and the program is run. Information about residuals and variable changes between iterations is displayed while the program is solving a problem. When a problem has converged within some set criteria, a solution is displayed in a separate window.

Useful features of the program include the ability to make parametric studies, multivariate min/max optimizations, plotting capability, export to spreadsheets, and several traditional programming elements such as functions, procedures, if-then-else blocks, looping structures, and goto statements. EES can also call user-written external code resources.

Modeling thermodynamic systems requires accurate information about fluid properties. EES has properties for many pure fluids and some mixtures, but the data for helium at cryogenic temperatures and high pressures was not accurate enough for our application. To solve this problem, the commercial helium property package HEPAK© was translated from Fortran 77 into Pascal and compiled into a code resource. The result is an external code resource named HeProp that EES calls for helium property data. A similar code resource named GasProp, based on GASPAK©, contains property data for other fluids. HEPAK© is based on NIST Technical Note 1334 (1991) [2,3]

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Modeling Cryogenic Processes at Fermilab

The main area of interest is simulation of the various operational modes of the Fermilab Tevatron Satellite Refrigerators, described elsewhere.[4] Models describing these liquid helium refrigerators can consist of 100-150 simultaneous nonlinear equations. With reasonable initial guesses, typical solution times are 5-6 minutes using a Macintosh™ IIsi (68030 CPU @ 20 MHz) with a floating point math coprocessor. The model includes a liquid nitrogen precooler, heat exchanger with internal gas reciprocating expander, liquid reciprocating expanders and JT valves, magnet systems, direct liquid injection and mixing, cold vapor compressors, and warm compressors. The heat exchanger is based on a model by Soyars [5], and includes variable pressure drop in both tube and shell side flows.

The main operating modes of the Satellite Refrigerators are 20 K cooldown, 10 K cooldown, liquefier, and refrigerator. Simulation of refrigeration mode agrees well with work done by Soyars and Rode, and simulation of liquefier mode agrees well with results by Rode. [5,6]

Figure 2 shows the results from the equation set shown in Figure 1. A 304 S.S. tube with internal heat generation and helium vapor cooling is modeled. The heat conducted into the cold end as a function of helium flow rate and electrical current is plotted. Many of the useful features described earlier are implemented in this equation set.

Other systems modeled to date include vapor pressure thermometers and cryogenic dewars undergoing overpressure relief. Finite element techniques are easily implemented when simulating heat exchangers. The thermophysical property data available in HEPAK© and GASPAK© allows users to simulate conditions ranging from the triple point to 2000 K and 1000 MPa for certain fluids. Combining this data transparently with EES© allows non-programmers to model a wide variety of engineering problems.

Acknowledgments

The guidance and advice of Jay Theilacker and Bill Soyars of Fermilab and Dr. Sandy Klein of F-Chart Software is greatly appreciated.

References

1. Engineering Equation Solver User Guide. F-Chart Software, Middleton, WI (1989)

2. HEPAK User Guide. Cryodata Inc., Niwot, CO (1991)

3. GASPAK User Guide. Cryodata Inc., Niwot, CO (1991)

4. Rode, C. Tevatron Cryogenic System, "12th Inter. Conf. of High Energy Accel.", 1983

5. Soyars, W. The applicability of constant property analyses in cryogenic helium heat exchangers, "Advances in Cryogenic Engineering," Vol. 37A, Plenum Press, New York (1991), p. 217.

6. Rode, C., Brindza, P., Richied, D. and Stoy, S. Energy Doubler Satellite Refrigerator Magnet Cooling System, "Advances in Cryogenic Engineering," Vol. 25, Plenum Press, New York (1980), pp. 326-334.

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Tcold = 5    {K};    Thot = 290   {K};    Pgas = 1    {Atm};   Mgas =1.7e-4  {g/s}
Length = 1    {m};    Elements = 50;    dx = Length / Elements    {m};   I = 1  {Amps}
OD = 0.01    {m};    ID = 0.009    {m};    G = Mgas/IFA
CSA=pi*(OD^2-ID^2)/4          {Tube material cross sectional area in m^2}
ISA=pi*ID*dx                  {Tube inside surface area in m^2}
IFA=pi/4*ID^2                 {Tube inside flow area in m^2}
TGas[0] = Tcold;    TWall[elements+1] = Thot {K};    TWall[0] = Tcold
x[0] = 0;    x[elements+1] = Length
duplicate z=1,elements
  x[z] = dx/2 + (z-1)*dx
  TFilm[z] = (TGas[z-1]/4+TGas[z]/4+TWall[z]/2)
  HTcoeff[z] = HTC(TFilm[z],PGas,MGas,IFA,dx)
  RE[z] = G*ID/CryoHeliumViscosityPT(Pgas,TFilm[z])
  Qinternal[z] + Qcondin[z] = Qconvection[z] + Qcondout[z]
     Qinternal[z] = I*I*dx*RhoSS(TWall[z])/CSA
     Qconvection[z] = HTcoeff[z]*ISA*(TWall[z]-(TGas[z]+TGas[z-1])/2)
     Qcondin[z] = (IKdT(TWall[z+1])-IKdT(Twall[z]))*CSA/(x[z+1]-x[z])
     Qcondout[z] = (IKdT(TWall[z])-IKdT(Twall[z-1]))*CSA/(x[z]-x[z-1])
  Qconvection[z] = (HfPT(PGas,TGas[z])-HfPT(PGas,TGas[z-1]))*MGas
end
```

Figure 1   Sample Equation Set

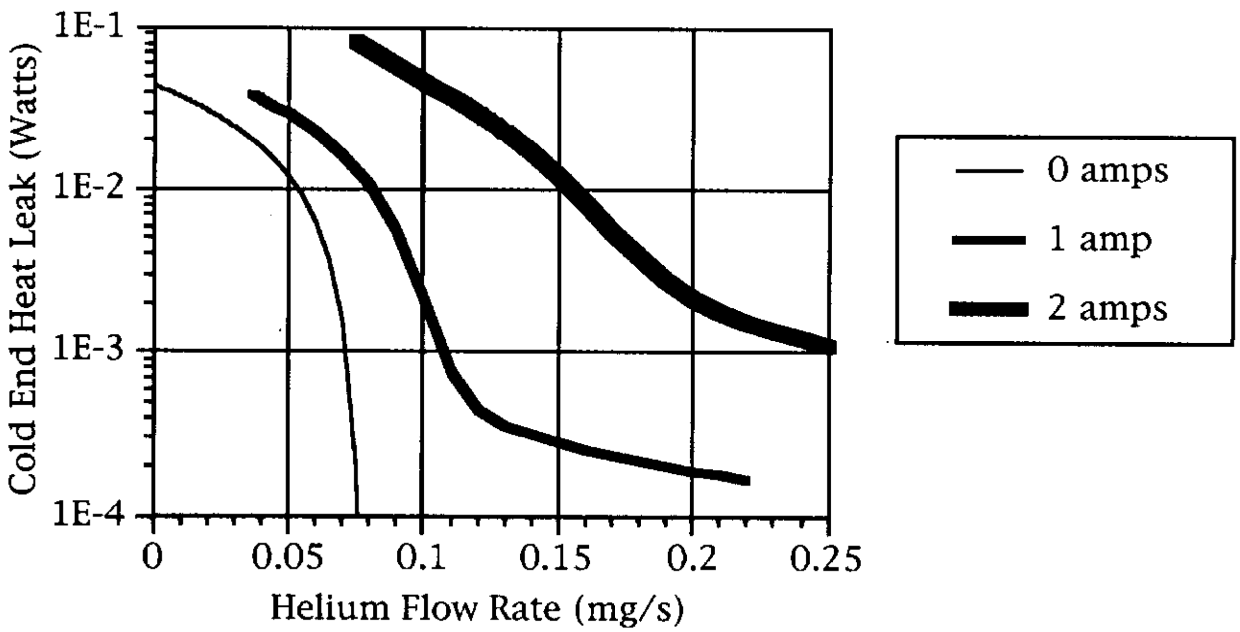

Figure 2: Cold End Heat Leak vs. Helium Flow Rate